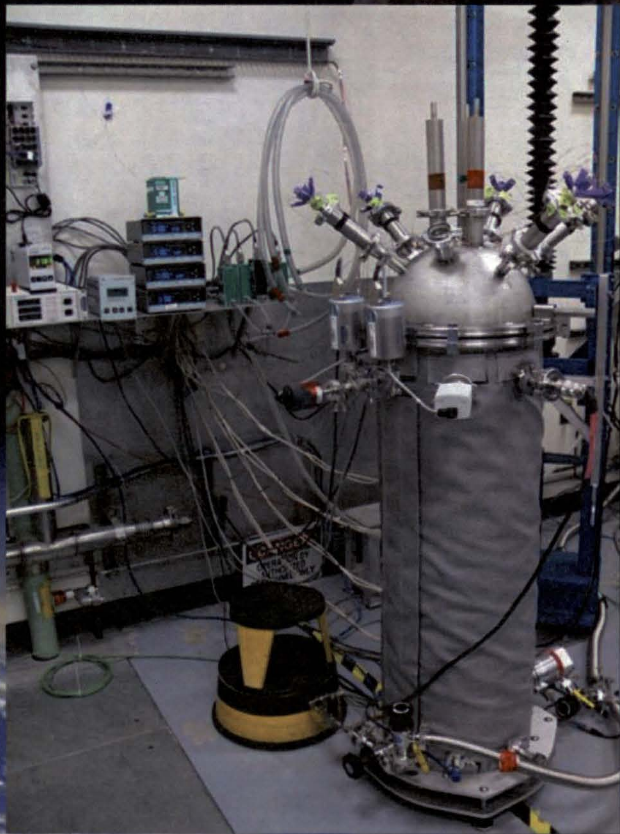
National Aeronautics and Space Administration

Penetration Degradation Calorimetry Industry Overview

Date TBD



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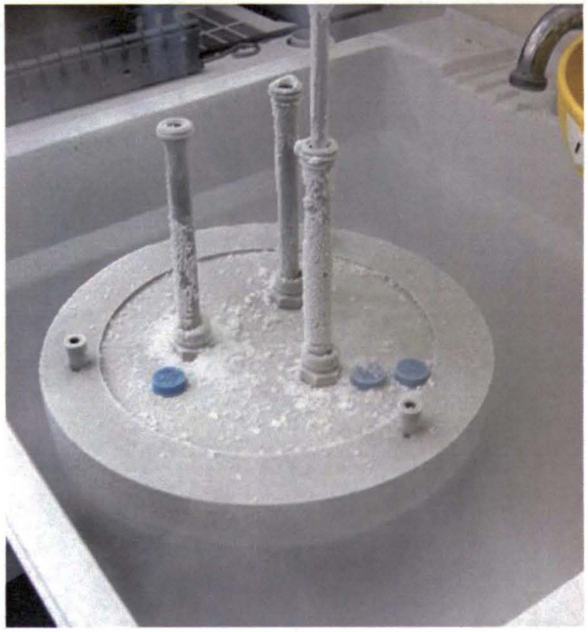
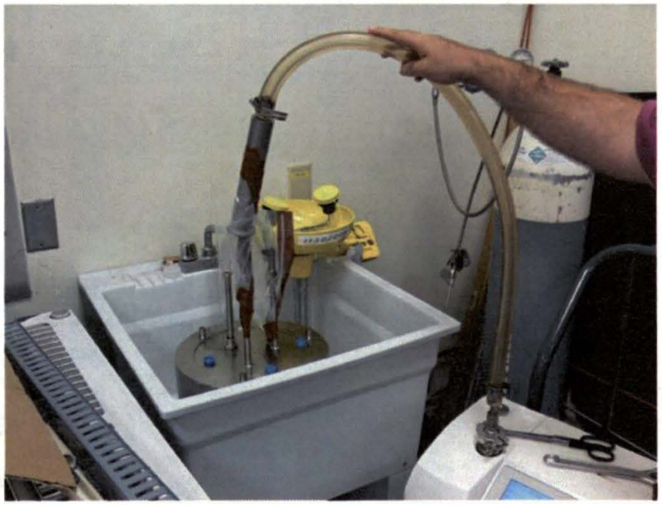
Agenda

- **Test Purpose and Objectives**
- **Technical Goals**
- **Test Approach**
- **Hardware Configuration**
  - Experimental Uncertainty
- **Test Matrix**
- **Sample Test Data**
- **Modeling**
- **Results**
  - No Penetration Repeatability
  - Materials Trade
  - Methodology Trade
  - Scaling Testing
  - Modeling
- **Summary**
- **Forward Work**





Test Purpose and Objective

- **Test Objective is to quantify heat losses with integrating MLI into real life situations**
  - The specific focus is on penetrations through the MLI
    - Load bearing structure
    - Electrical conduit
    - Fluid lines (fill/drain/pressure taps)

- **The purpose of the test is to provide experimental data…**
  - To validate thermal models
  - To estimate integration thermal losses associated with MLI and penetration

Technical Goals

The success of the project will be measured by two Key Performance Parameters (KPPs):

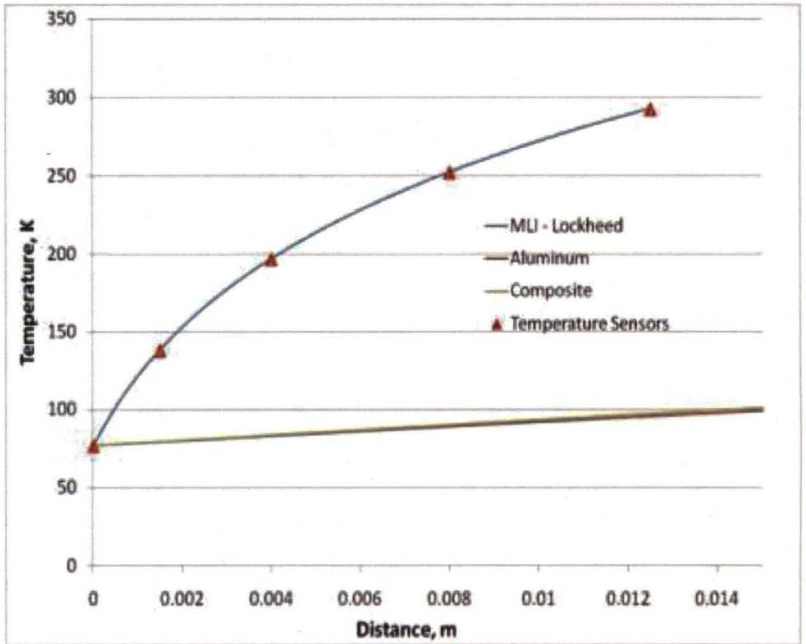
- **Degradation radius (m) – the radius of the area of MLI degradation will be less than:**
  - This generally starts at the center of strut and assumes a 13 mm diameter strut
  - Minimal Success: 0.05 m (400% of strut diameter)
  - Full Success: 0.02 m (150% of strut diameter)
- **System delta Q (W) – the differential power input between the test and the undisturbed insulation + penetration conduction:**
  - Minimal Success: < 0.2 W
  - Full Success: < 0.1 W

Test Approach

- **Goal: Determine ΔQ due to integration**
  - Measure plain MLI blanket thermal performance (No Penetration)

$$Q_{MLI} = V\rho h_{fg}$$

  - Know penetration material thermal properties and geometry
  - Measure temperature gradient down the penetration



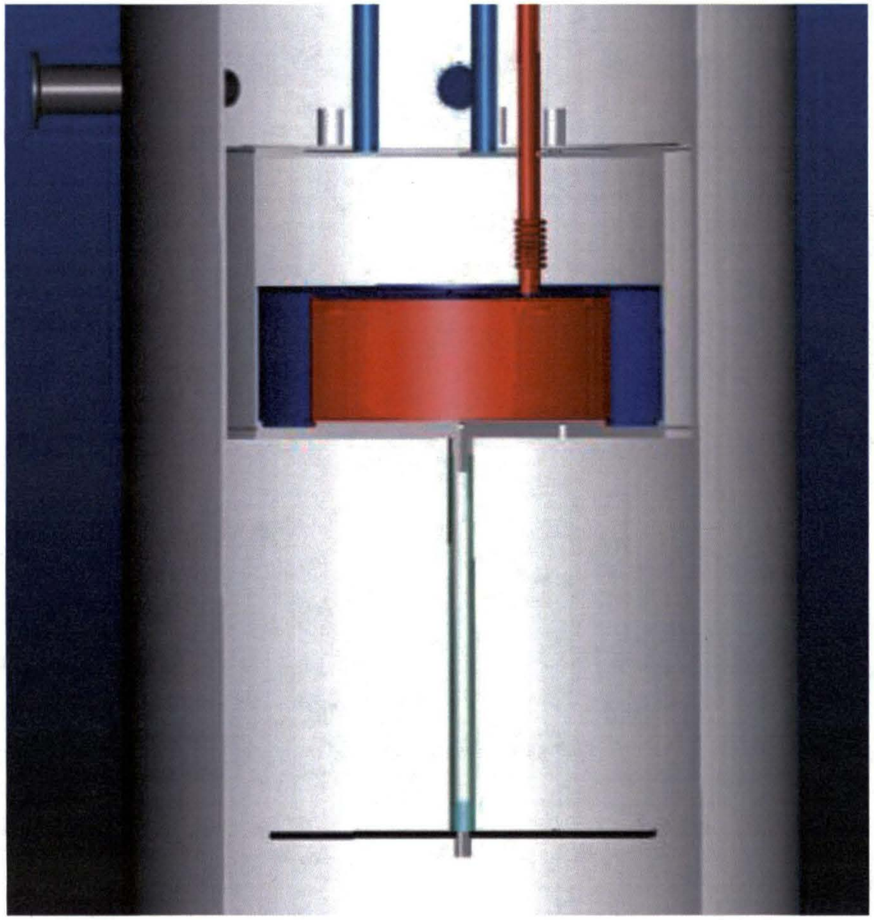
$$Q_{Strut} = \frac{k\ A\ (\Delta T)}{x}$$

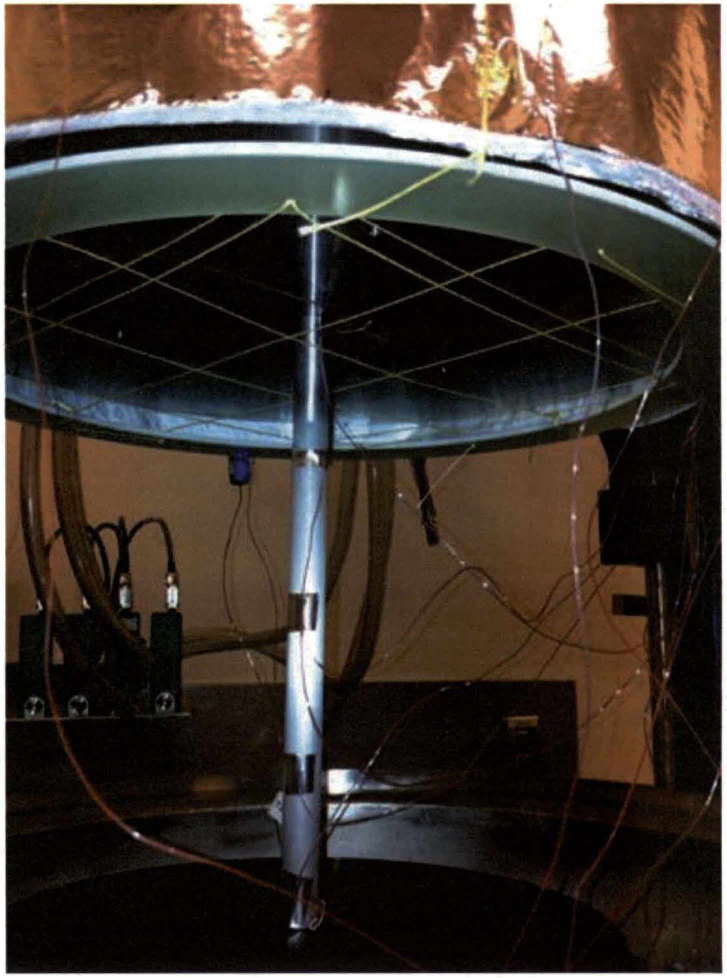
  - Measure total system heat load $Q_{Meas} = V\rho h_{fg}$
  - Subtract out knowns to get integration losses

$$\Delta Q_{Pen} = Q_{meas} - Q_{MLI} - Q_{Strut}$$

- **Goal: Determine effected zone**
  - Measure MLI temperatures radially outward on four different layers
    - Layers 3, 8, 16, & 25
    - At MLI ID (if no penetration, then r = 0), 25 mm, 51 mm, 102 mm

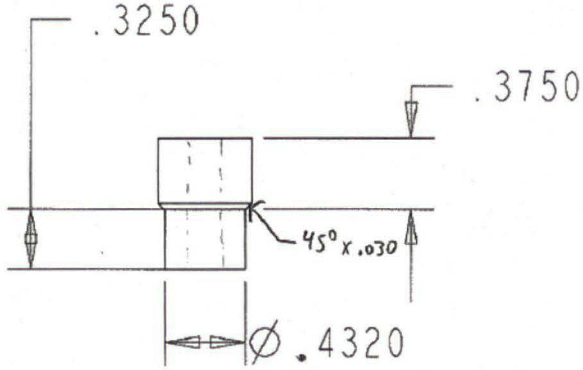
Hardware Configuration



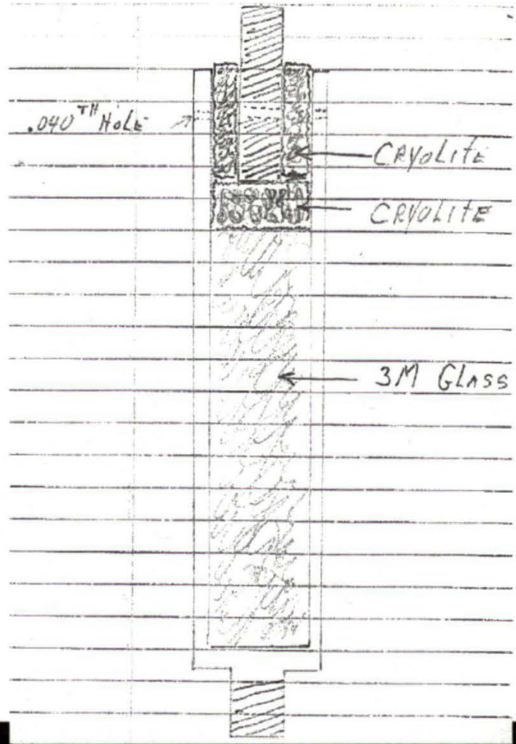


Strut/penetration configurations

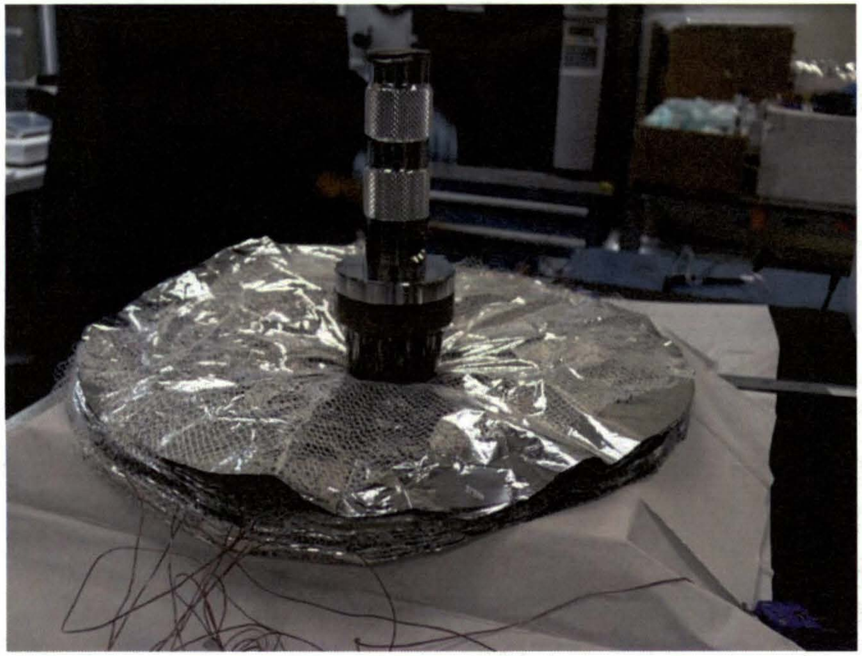
- **Used three different aluminum 6061 struts (standard tubing)**
  - 0.5" OD x 0.035" wall strut
  - 0.25" OD x 0.035" wall strut
  - 1.0" OD x 0.049" wall strut
  - Internals diagramed on right

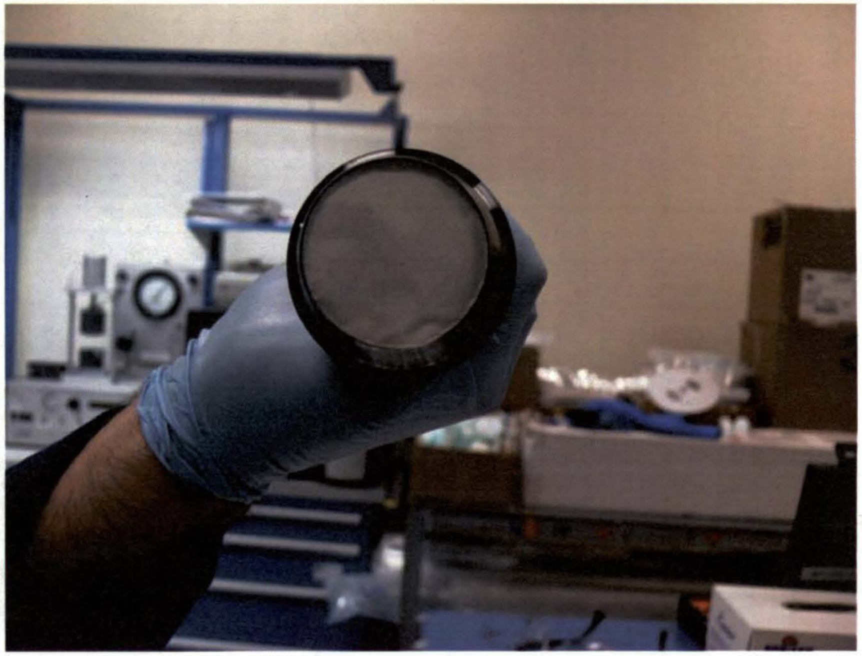


- **Composite strut**
  - Made from tube material (2 ply) with warp direction down the length of the strut (1K carbon fiberglass)
  - 1.060" OD
  - 0.032" wall (0.996" ID)
  - Wrapped on a 1" mandrel

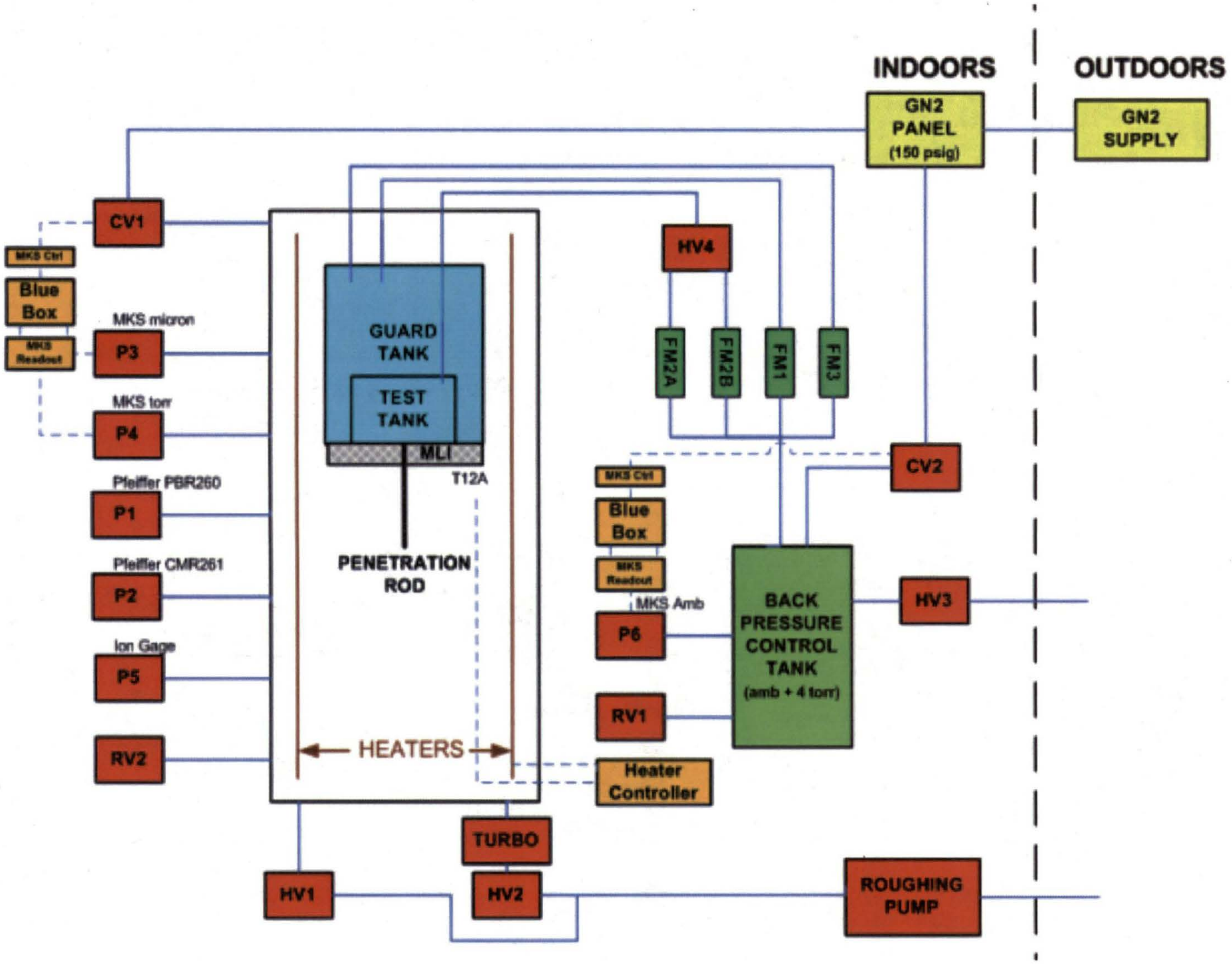


Punching a Hole



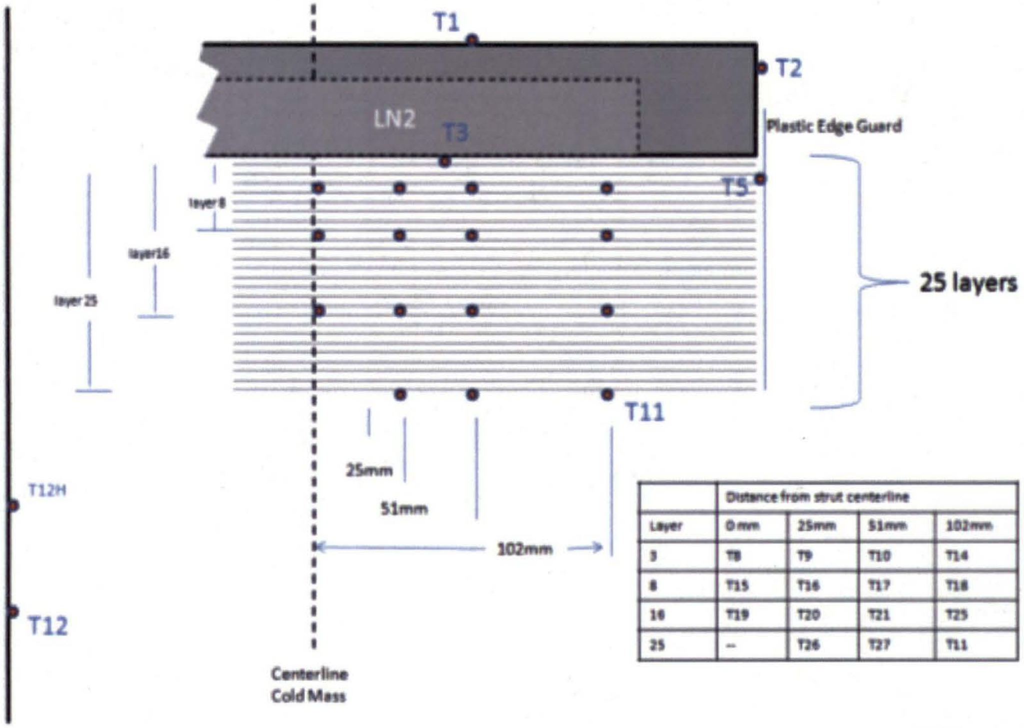


Schematic

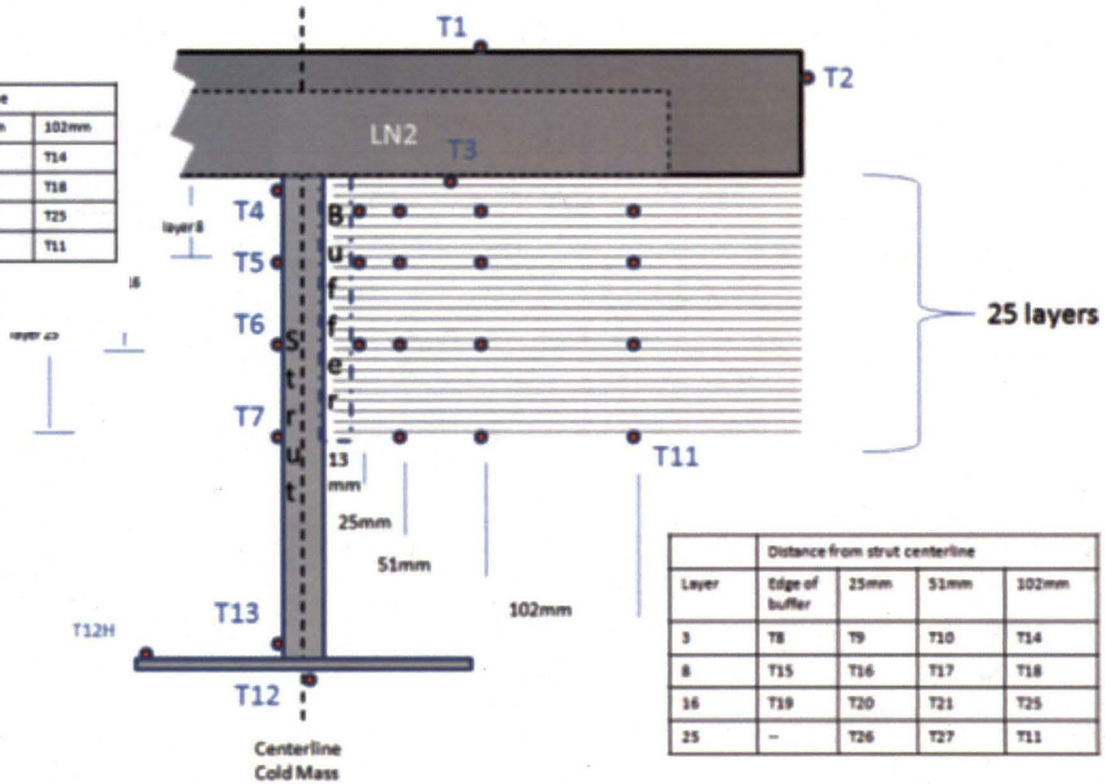


INDOORS
OUTDOORS
GN2 PANEL (150 psig)
GN2 SUPPLY
CV1
MKS Ctrl
Blue Box
MKS Readout
MKS micron
P3
MKS torr
P4
Pfeiffer PBR260
P1
Pfeiffer CMR261
P2
Ion Gage
P5
RV2
GUARD TANK
TEST TANK
MLI
T12A
PENETRATION ROD
HEATERS
HV4
FM2A
FM2B
FM1
FM3
CV2
MKS Ctrl
Blue Box
MKS Readout
MKS Amb
P6
RV1
BACK PRESSURE CONTROL TANK (amb + 4 torr)
HV3
Heater Controller
TURBO
HV1
HV2
ROUGHING PUMP

Temperature Sensors



	Distance from strut centerline			
Layer	0 mm	25mm	51mm	102mm
3	T8	T9	T10	T14
8	T15	T16	T17	T18
16	T19	T20	T21	T25
25	--	T26	T27	T11



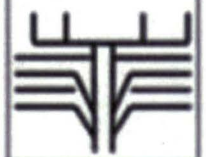
	Distance from strut centerline			
Layer	Edge of buffer	25mm	51mm	102mm
3	T8	T9	T10	T14
8	T15	T16	T17	T18
16	T19	T20	T21	T25
25	--	T26	T27	T11

Uncertainty Analysis

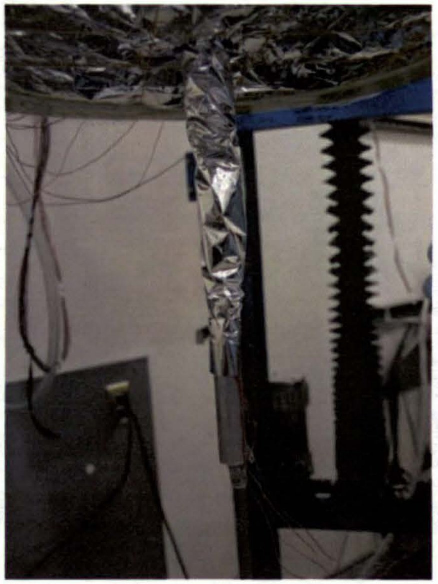
$$U_{\Delta Qpen}=\sqrt{\begin{array}{l}\left(\frac{kA\Delta T}{x}\right)^2\left[\left(\frac{U_k}{k}\right)^2+\left(\frac{U_A}{A}\right)^2+\left(\frac{U_{\Delta T}}{\Delta T}\right)^2+\left(\frac{U_x}{x}\right)^2\right]\\ +2\left(\rho h_{fg}V\right)^2*\left[\left(\frac{U_V}{V}\right)^2+\left(\frac{U_\rho}{\rho}\right)^2+\left(\frac{U_{hfg}}{h_{fg}}\right)^2\right]\end{array}}$$

			Test	Test P103		Test P105		Test P113		Test P116		Test P104		Test P101	
			MLI Serial Number	SN 002		SN 002		SN 006		SN 006		SN 002		SN 002	
			Description	1/2" strut, 1/4" thick buffer		1/2" strut, 1" thick AG buffer		1/4" strut, 1/4" thick Cryolite buffer		1" strut, 1/4" thick Cryolite buffer		1/2" strut, 1/2" vacuum buffer		1/2" strut, 1/8" vacuum buffer	
	Uncertainty Term	Related Parameter	Units	Relative Uncertainty Ux/x	Nominal Value	Relative Uncertainty Ux/x	Nominal Value	Relative Uncertainty Ux/x	Nominal Value	Relative Uncertainty Ux/x	Nominal Value	Relative Uncertainty Ux/x	Nominal Value	Relative Uncertainty Ux/x	Nominal Value
Thermal Conductivity	$\frac{U_k}{k}$	k	W/m-K	0.005	133.9	0.005	133.93	0.005	106.9	0.005	124.2	0.005	132.4	0.005	135.6
Volumetric Flow Rate	$\frac{U_V}{V}$	Vmeas	sccm	0.05	956.7	0.05	766	0.05	154.6	0.05	463.7	0.05	963.8	0.05	796.9
		VMLI	sccm		31		31		71		71		31		31
Density	$\frac{U_\rho}{\rho}$	ρ	Kg/m^3	0.0223	1.167	0.0223	1.167	0.0223	1.167	0.0223	1.167	0.0223	1.167	0.0223	1.167
Vaporization	$\frac{U_{h_{fg}}}{h_{fg}}$	h_{fg}	kJ/kg	0.02	199.2	0.02	199.2	0.02	199.2	0.02	199.2	0.02	199.2	0.02	199.2
Heat Transfer	$\frac{U_x}{x}$	x	m	0.0019	0.18603	0.0020	0.1752	0.0043	0.082	0.0032	0.1115	0.0019	0.18603	0.0020	0.1752
Area of Strut	$\frac{U_A}{A}$	A	m^2	0.0003	3.04E-05	0.0003	3.04E-05	0.0002	1.53E-05	0.0003	9.44E-05	0.0003	3.04E-05	0.0000	0.00E+00
Temperature Difference	$\frac{U_{\Delta T}}{\Delta T}$	ΔT	K	0.0211	133.9	0.0325	87	0.1230	23	0.0232	121.7	0.0215	131.7	0.0228	123.8
Heat Leak	Q		W	-	3.96	-	3.17	-	0.64	-	1.919	-	3.988	-	3.298
Total Uncertainty				0.0651		0.0673		0.0564		0.3072		0.0643		0.0108	
Percent Uncertainty				1.643%		2.124%		8.807%		16.006%		1.613%		0.328%	

Test Matrix

Test	Test Description	Reason	Figure
1	No Penetration	Baseline	
2	No Integration a) Without gap b) With gap (a no buffer case)	Worst Case	
3	Isolated Penetration a) 1/2" Aerogel Blanket b) ½" Bead Pack c) 1" Aerogel Blanket d) ½" CryoLite e) 1" CryoLite	Isolate bulk insulation from penetration insulation	
4	Temperature Matched a) Lockheed b) Test #1	Best Case (assumes single warm temperature)	
5	Variable Size a) 0.25" strut with best from above b) 5a. disturbed MLI c) 1" strut with best from above	Change size of strut	
6	Composite Strut a) Isolated b) No Adaption	Change penetrations conductivity	

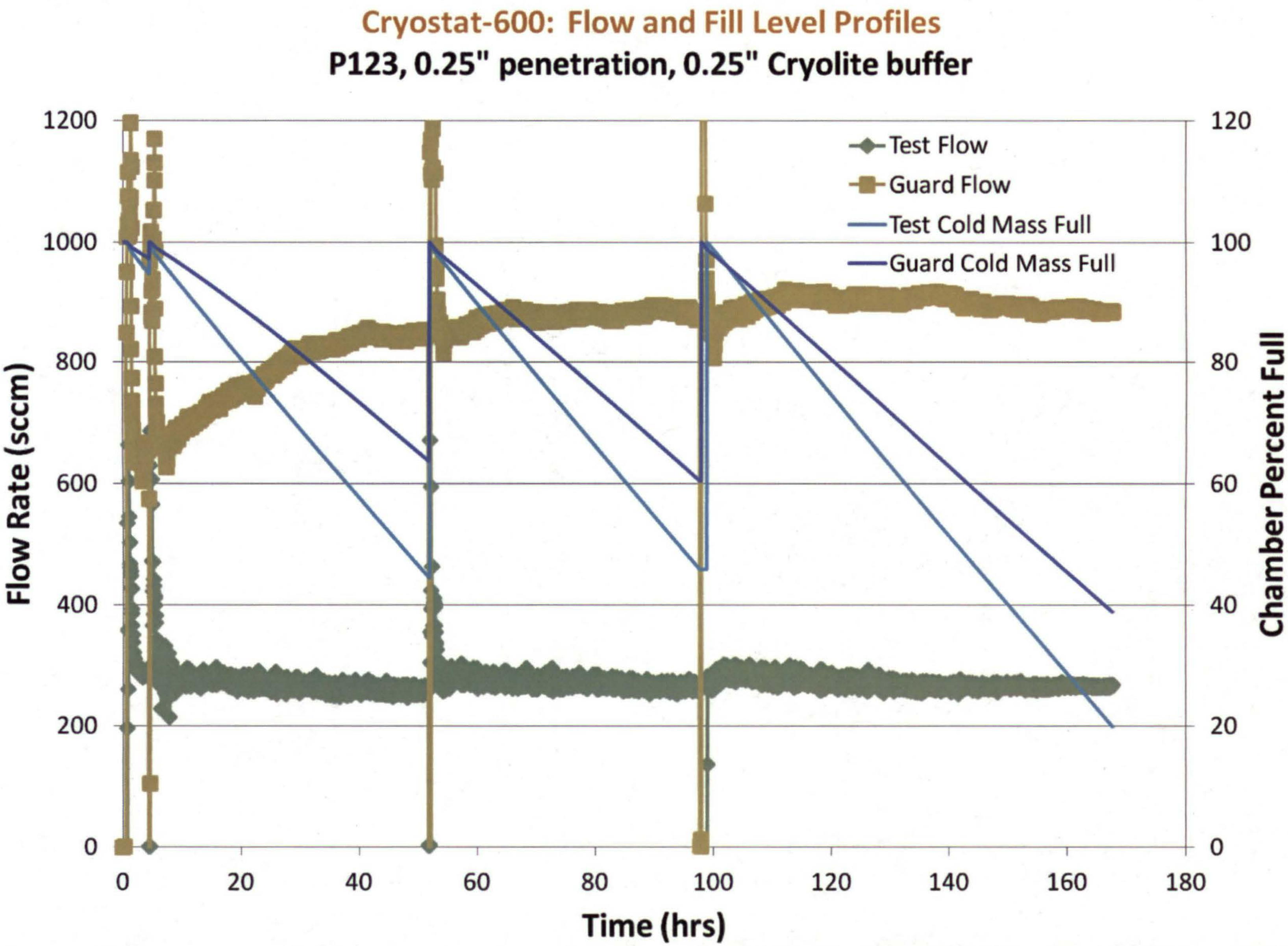
Aerogel bead pack



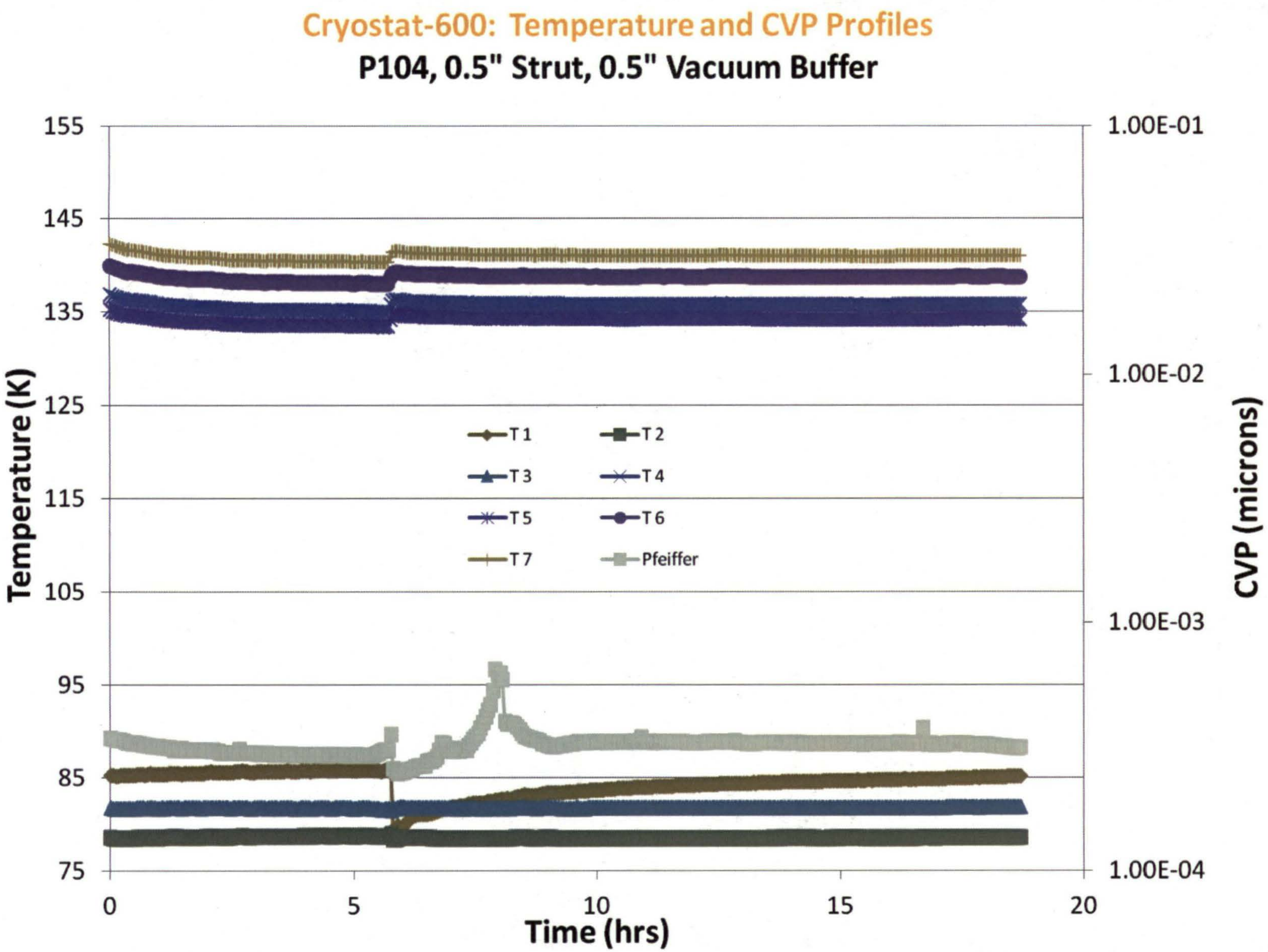
Temperature Matching

No Penetration

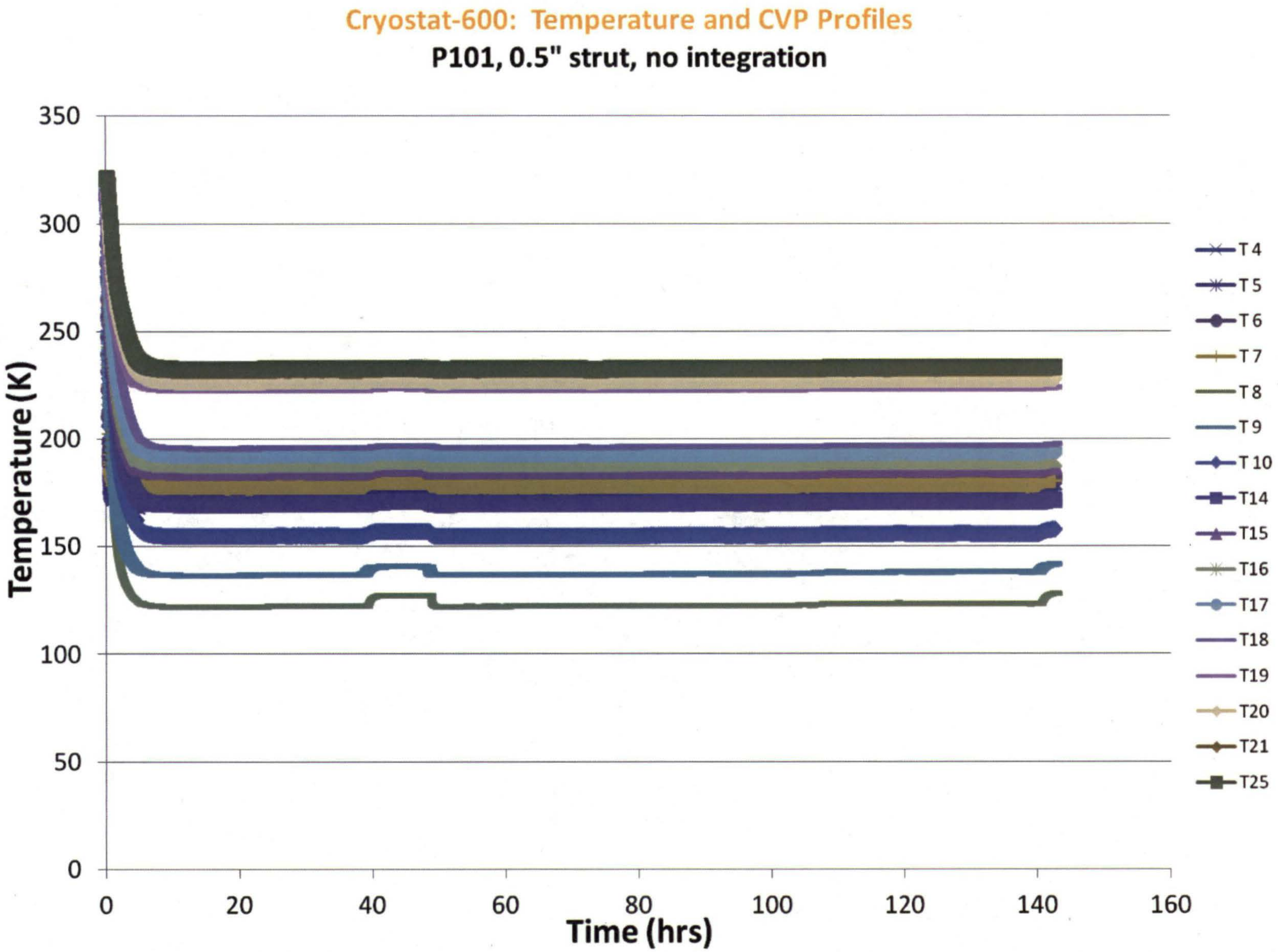
Sample Test Data - Flows



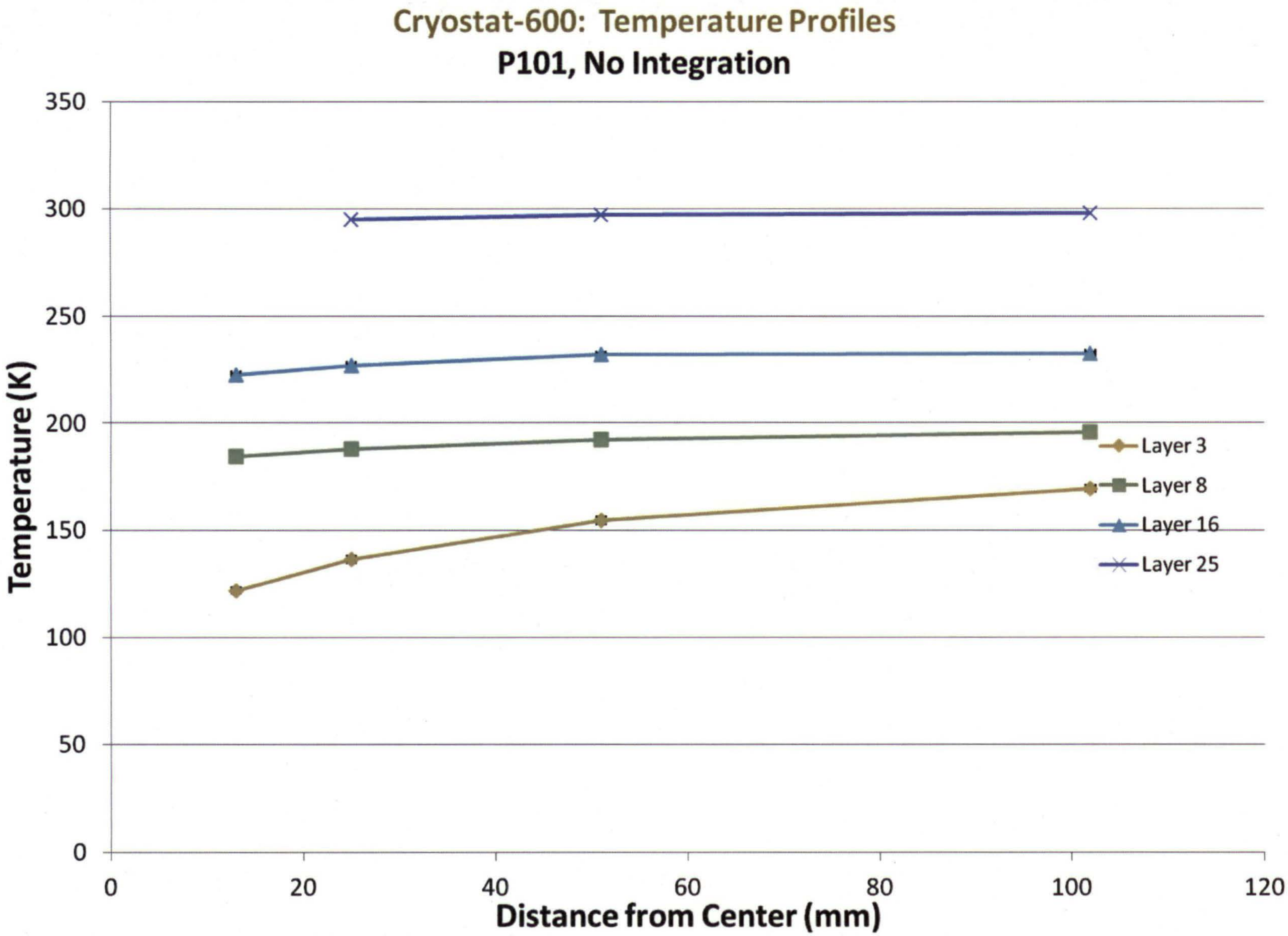
Sample Test Data – Temperatures & Vac Pressure



Sample Test Data – MLI Temperatures



Sample Test Data – MLI 2-D Temperatures

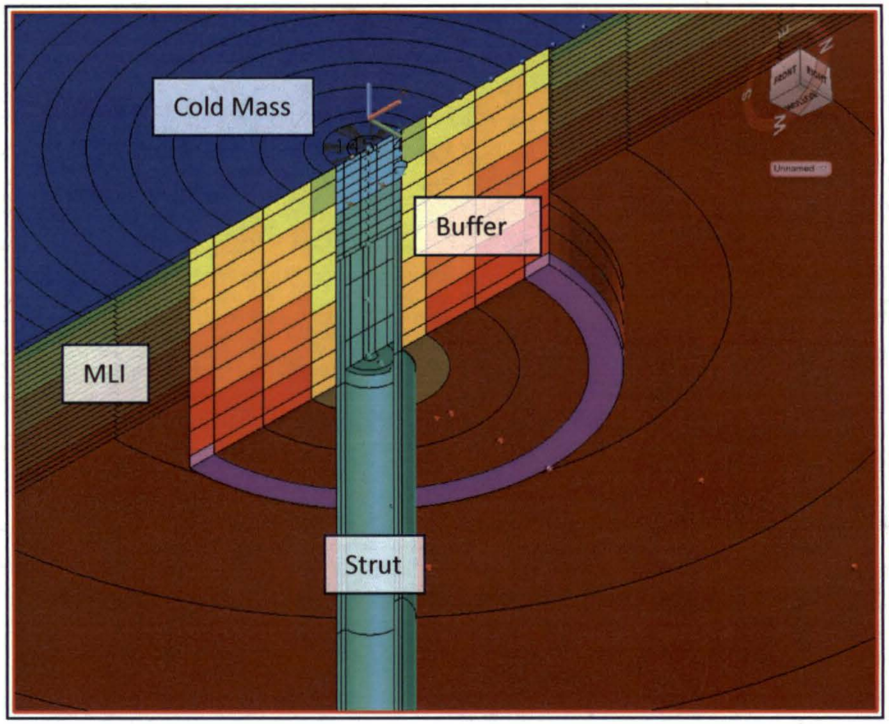


Modeling – For Validation

Detailed thermal models of the tests were developed in Thermal Desktop (using Sinda/Fluint)

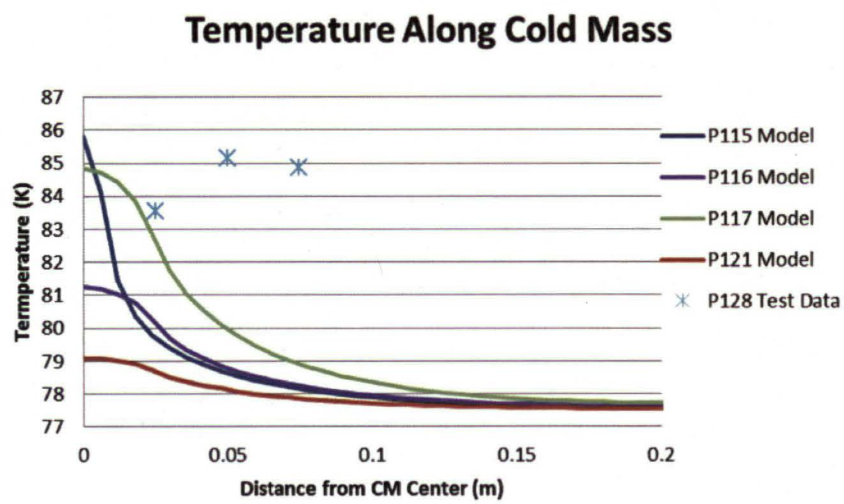
The detailed model includes the components of the cold mass including:

- **Test and guard chambers**
- **Insulation surrounding the guard chamber**
- **Fill tubes**
- **Penetration**
- **Penetration insulation**
- **Passive Heater**
- **Edge Guard**
- **Test section of MLI**
- **G10 MLI support ring**



Modeling - Details

- **MLI**
  - Each layer of MLI was modeled as an individual surface
  - Used radial nodes (assumed no theta dependence)
  - Conduction between nodes on same layer
  - Conduction and Convection between layers modeled with Lockheed Equation (4-56) with degradation factor
  - Radiation between layers modeled using Thermal Desktops' radiation solver (RadCad)
  - "Temperature Sensors" were placed in the MLI at similar locations to the actual test
- **Cold Mass**
  - Used saturated LN2 boundary nodes with convection turned on
  - Created a slight temperature peak at penetration
  - Saw this in temperature data as well
- **Penetration**
  - Dimensions taken from drawings



Model Validation

Temperature and heat load validation data is shown below

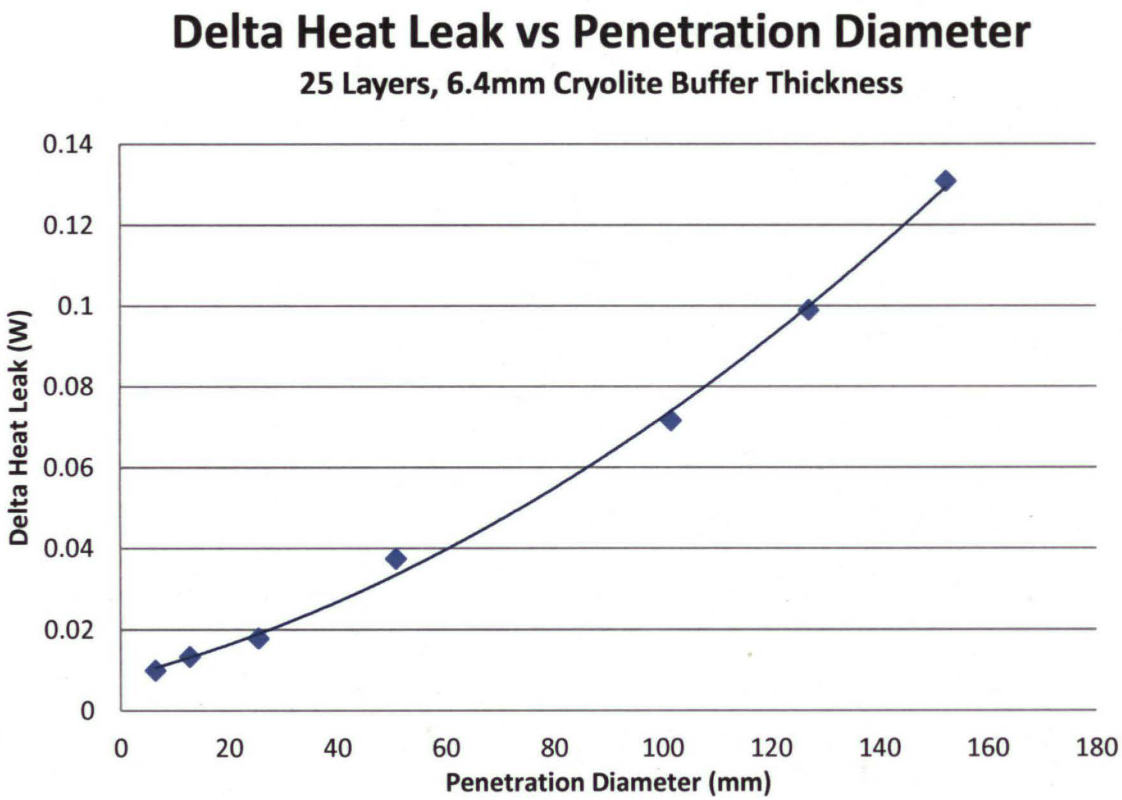
Test		Average Percent Error In Temperature Match Between Test Results And Model	
		Strut	MLI
12.7mm AL Strut, 25.4mm buffer	P106 Run 1	1.03%	1.87%
6.35mm AL Strut, 25.4mm buffer	P115 Run 1	1.03%	0.71%
25.4mm AL Strut, 12.7mm buffer	P116 Run 1	0.25%	2.96%
25.4mm AL Strut, 25.4mm buffer	P117 Run 1	0.23%	2.61%
25.4mm Composite Strut, 25.4mm buffer	P121 Run 1	2.13%	1.12%

Test		Penetration Heat Load	
		Test (W)	Model (W)
12.7mm (½") AL Strut, 25.4mm (1") buffer	P106 Run 1	2.906	0.844
6.35mm (¼") AL Strut, 25.4mm (1") buffer	P115 Run 1	0.645	0.916
25.4mm (1") AL Strut, 12.7mm (0.5") buffer	P116 Run 1	0.56	0.872
25.4mm (1") AL Strut, 25.4mm (1") buffer	P117 Run 1	1.476	1.78
25.4mm (1") Composite Strut, 25.4mm (1") buffer	P121 Run 1	0.153	0.397

Model – For Scaling

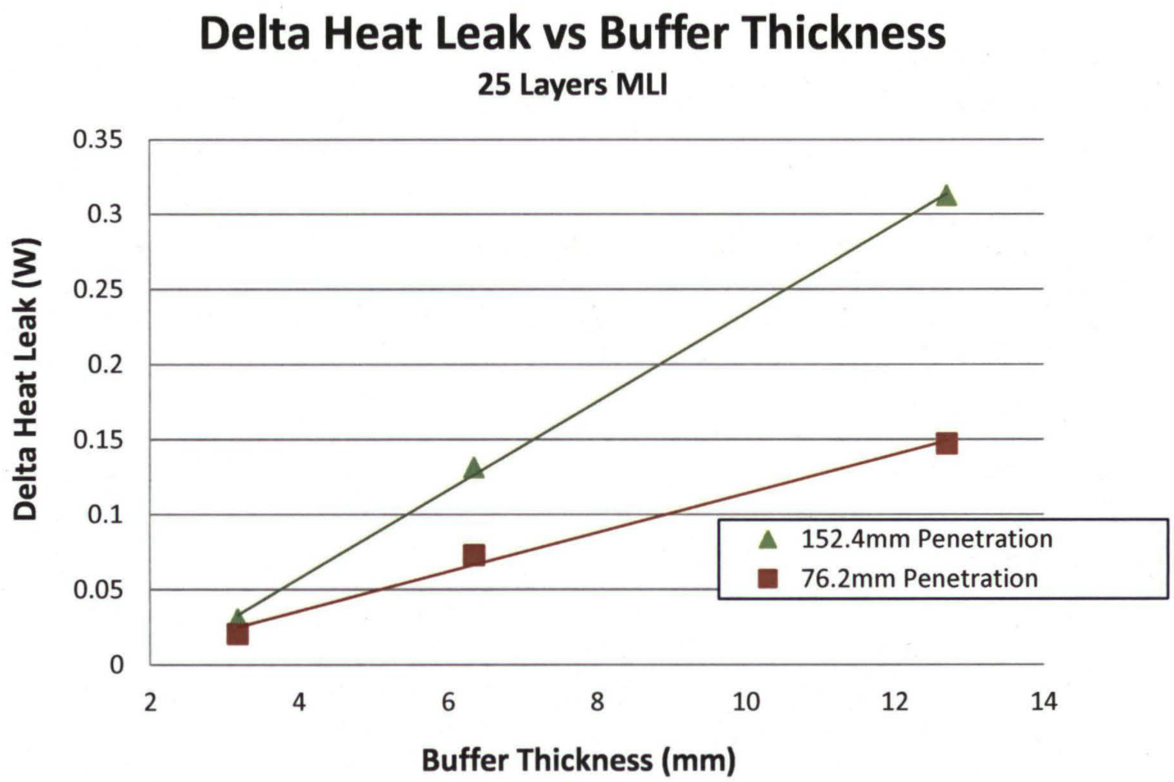
- **To scale outside of testing bounds a few changes were made:**
  - Calorimeter specific geometry was removed
    - Guard chamber
    - Edge effect containment
    - Etc
  - Flat plate extended so that much greater than penetration dimension

Model – Scaling - Diameter



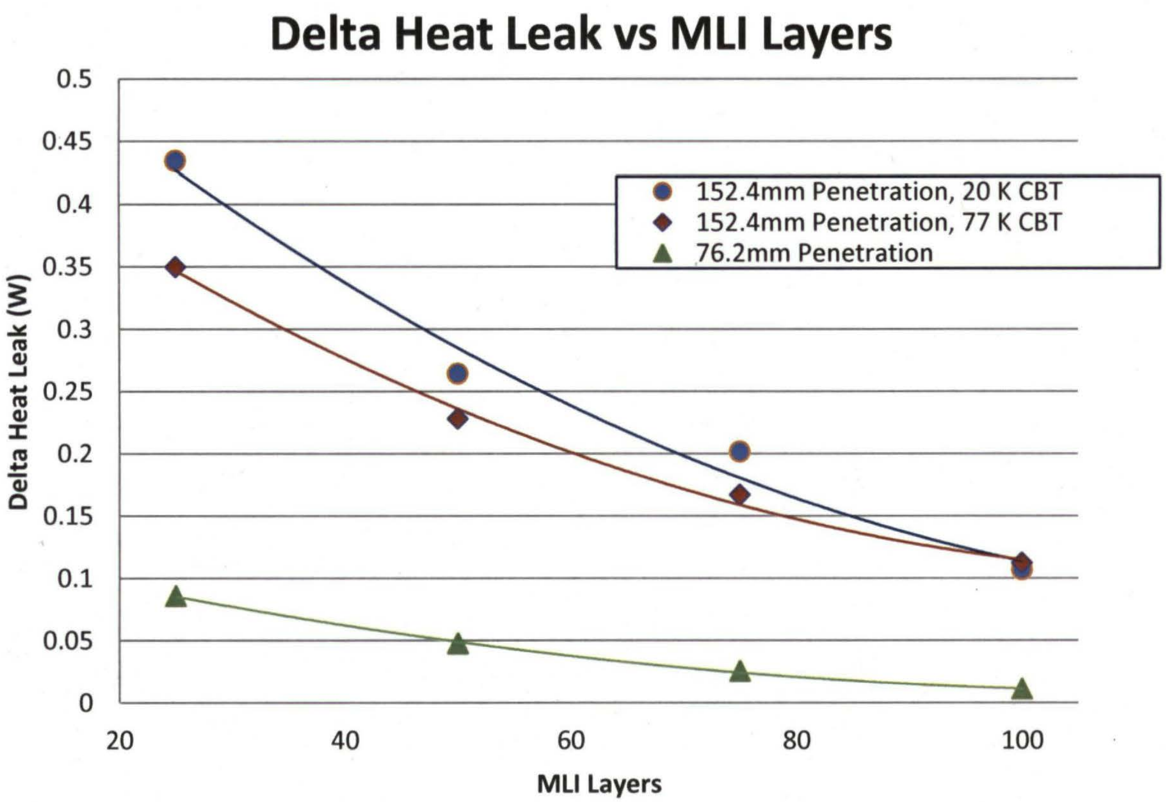
Penetration Details	Change in Heat Leak (W) with Strut Diameter (x in meters)
25 Layers, 6.4mm Cryolite Buffer	$2.95x^2 + 0.346x + 0.00826$

Model – Scaling – Buffer Thickness



Penetration and Environment	Change in Heat Leak (W) With Buffer Thickness (x in meters)
152.4 mm Strut, 25 Layers MLI	Y = 29. 5x – 0.0608
76.2 mm Strut, 25 Layers MLI	Y = 13.1x – 0.0168

Model – Scaling - # Layers



Penetration Details	Change in Heat Leak (W) With MLI Layers (x)
152.4mm Penetration, 25.4mm Buffer, 20 K Cold Boundary	$3.03E\text{-}5x^2 - 7.97E\text{-}3x + 0.607$
152.4mm Penetration, 25.4mm Buffer, 77 K Cold Boundary	$2.68E\text{-}5x^2 - 6.44E\text{-}3x + 0.491$
76.2mm Penetration, 12.7mm Buffer	$9.51E\text{-}6x^2 - 2.17E\text{-}3x + 0.134$

Results

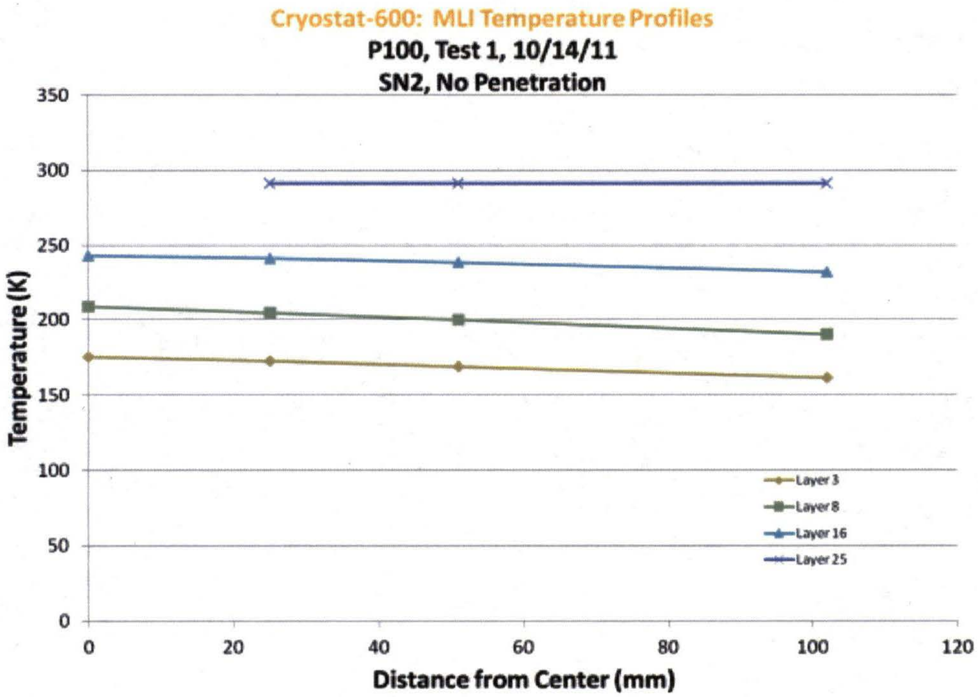
- No Penetration
- No Integration
- Buffer Material Trade
- Strut Size Trade
- Temperature Matching
- Composite Strut
- MLI Disturbance
- Modeling

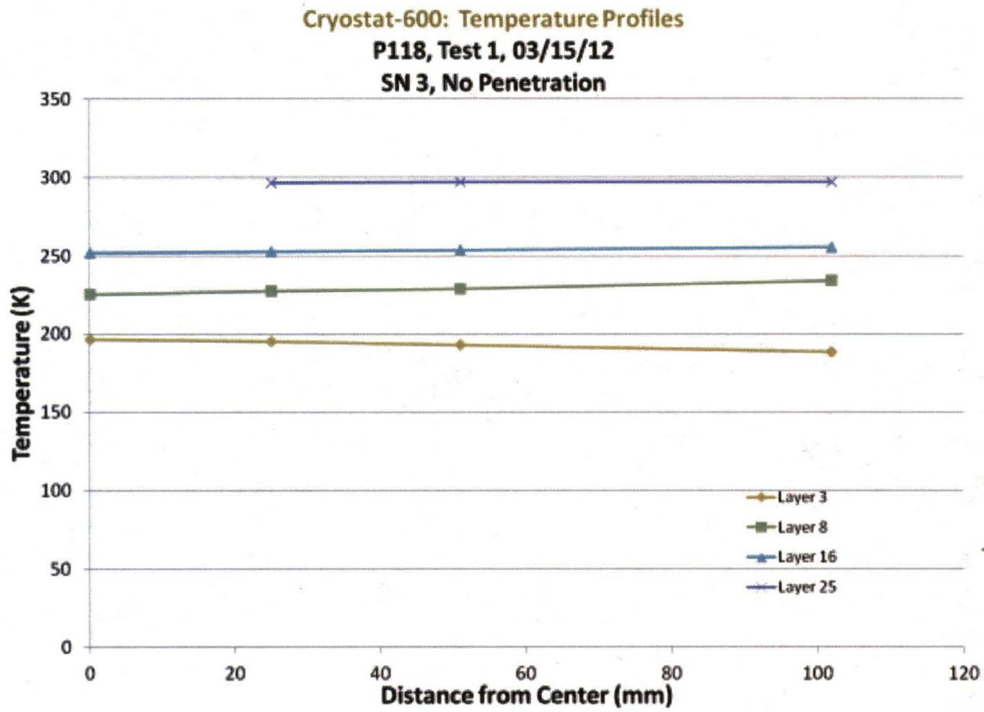
Results – No Penetration

- Tested 5 different MLI blankets
- Heat load depended on OD
  - When OD repeated, within 6% repeatability
  - Due to radiation tunneling in outer gap & conduction to guard ring
  - On P112 measured ~10 K lower temperature on green ring

Series #	Blanket Serial Number	Outer Diameter (mm)	Heat load (W)	Blanket Usage
P100	SN2	305	0.130	Buffer Materials
P107	SN3	305	0.122	None
P109	SN5	300	0.203	Temperature Matching
P112	SN6	285	0.294	Penetration Sizes
P118	SN3	297	0.194	Composite Strut
P122	SN7	300	0.191	Retesting

Results – No Penetration





Typical Temperature plots for no penetration testing

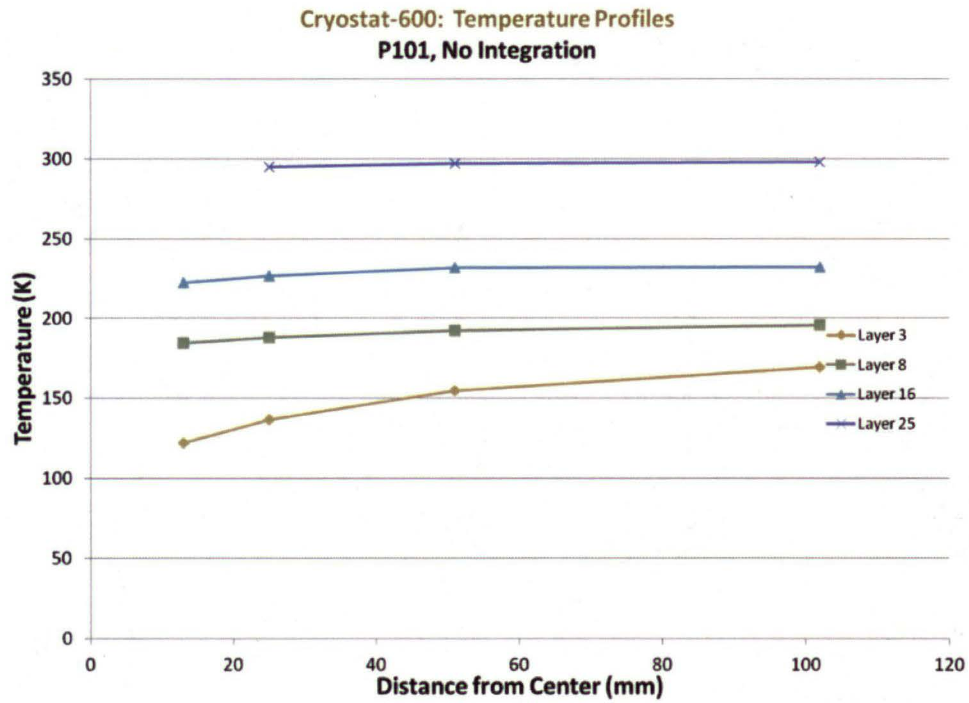
Each line is one layer of MLI

Shows heat flowing across layer(s)

Test on left is 305 mm diameter, test on right is 300 mm diameter

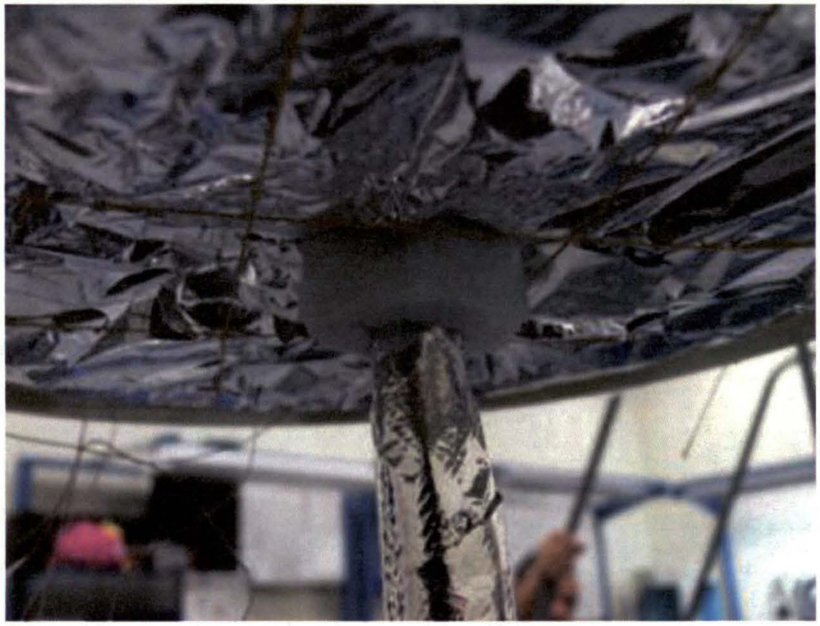
Results - No Integration

- Aluminum Strut
  - Punched 5/8” hole
  - ½” strut
  - Measured ΔQ of 0.50 W
  - Degraded radius over 100 mm
- Composite strut
  - Punched 1 1/16” hole
  - 1.020” diameter strut
  - Measured ΔQ of 0.31 W
  - Degraded radius over 100 mm



Aluminum Strut Data shown

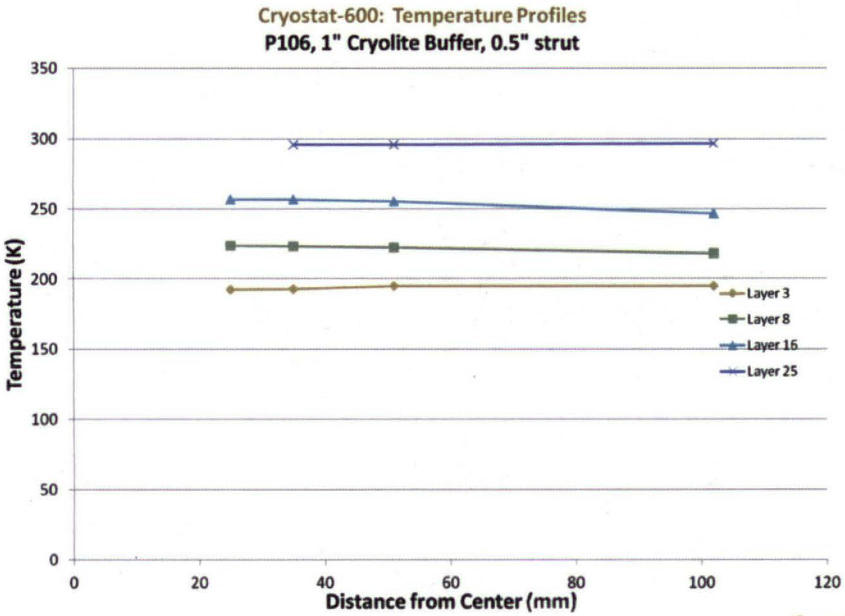
Results – Buffer Material Trade

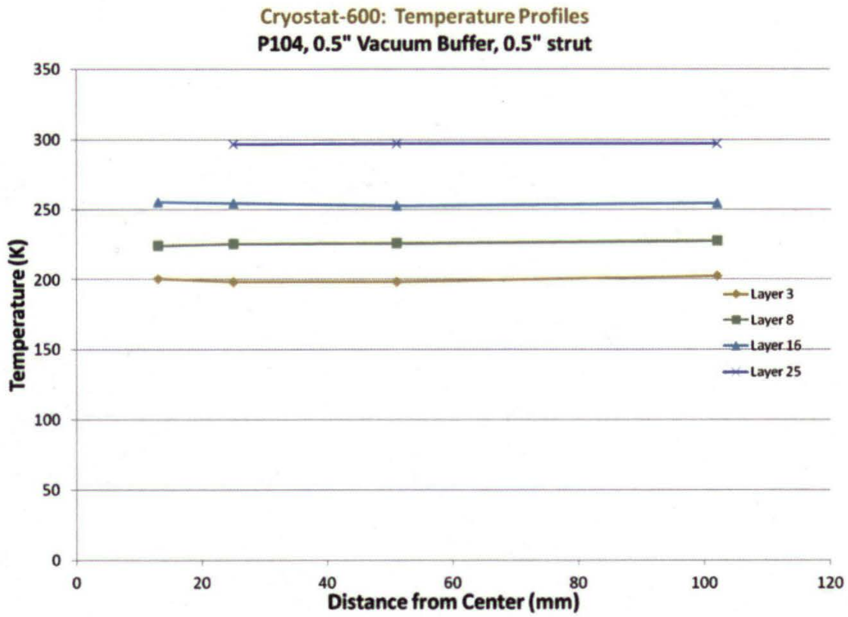


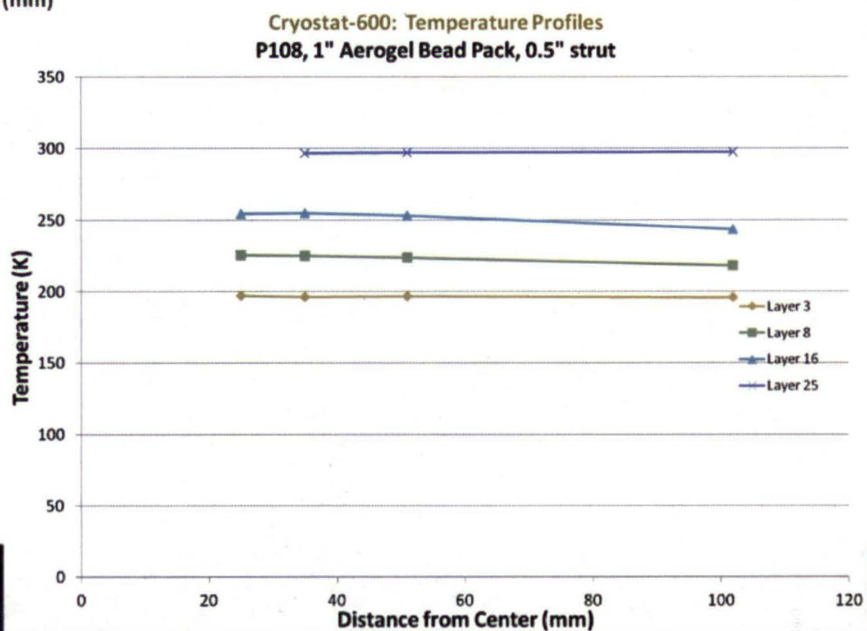
Material	ΔQ at 0.5" (W)	ΔQ at 1.0" (W)
Aerogel Blanket	0.764	0.942
Aerogel Beads	N/A	0.759
Cryolite	0.750	0.262
Vacuum	0.979	N/A

- Tested 3 materials and vacuum (i.e. gap but no buffer)
- Results indicate Cryolite best performer at all thicknesses
  - Significantly better at large thicknesses
  - Due to pliability
  - Thickness can be varied much easier than other materials investigated

Results - Buffer Material Trades







Results – Strut Size Trades

- Top table show test #s
- Middle table shows ΔQ in watts
- Bottom table shows degradation radius in mm
- For 0.25" strut, only need 0.25" buffer
- For 1" strut, 0.5" buffer required
- For 0.5" strut, somewhere in between
- Degradation radii had little to do with actual integration losses
  - Low conductivity of mylar

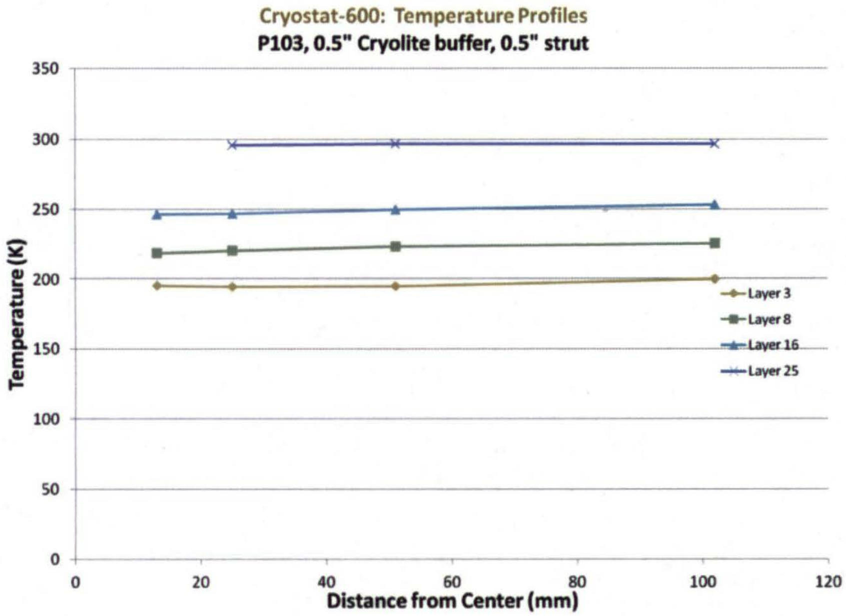
Cryolite Buffer material

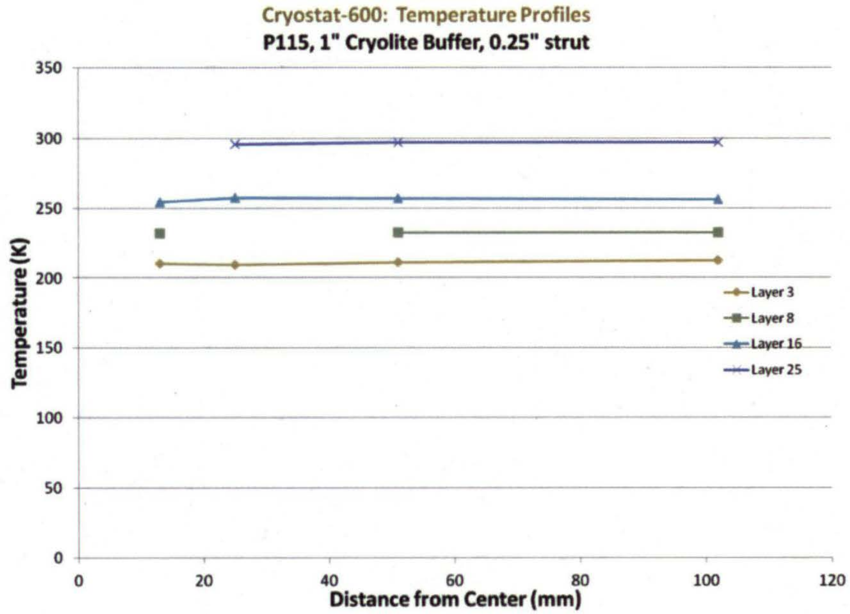
Aluminum 6061-T6 struts Test log		Buffer Thickness/radius, in 0.25	0.5
Strut Size, OD (in)	0.25	P113	P115
	0.5	P103	P106
	1	P116	P117

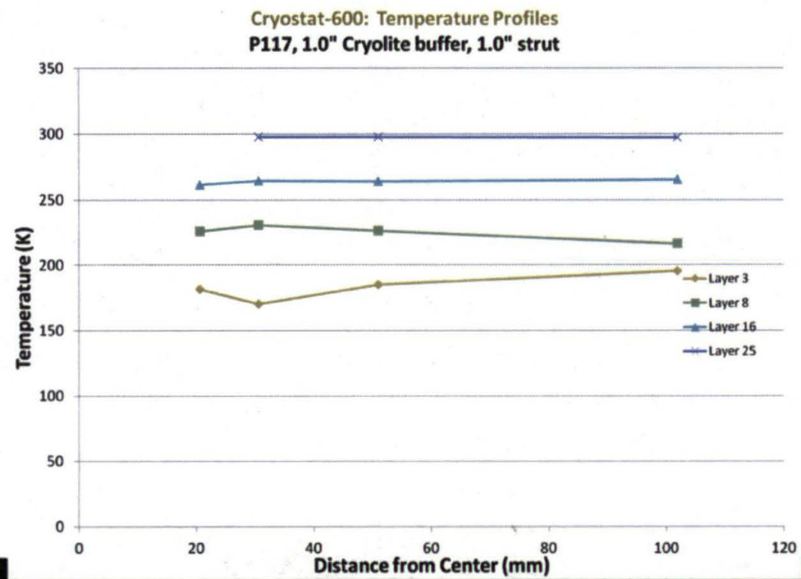
Aluminum 6061-T6 struts, dQ		Buffer Thickness/radius, in 0.25	0.5
Strut Size, OD (in)	0.25	0.200	0.288
	0.5	0.750	0.262
	1	0.656	0.231

Aluminum 6061-T6 struts, R effect		Buffer Thickness/radius, in 0.25	0.5
Strut Size, OD (in)	0.25	25	< 25
	0.5	51	<25
	1	>100	>100

Results – Strut Size Trades







Results – Warm Boundary Dependence

- On Test P116 (1 inch strut, 0.25" thick buffer) the warm boundary was increased to 325 K
- Minimal increase seen in degradation, both heat load and temperatures
- Results used to calculate power factor between warm boundary temperatures
  - A successfully used method on MLSTC to scale MLI performance
  - Power factor calculated to be 1.56

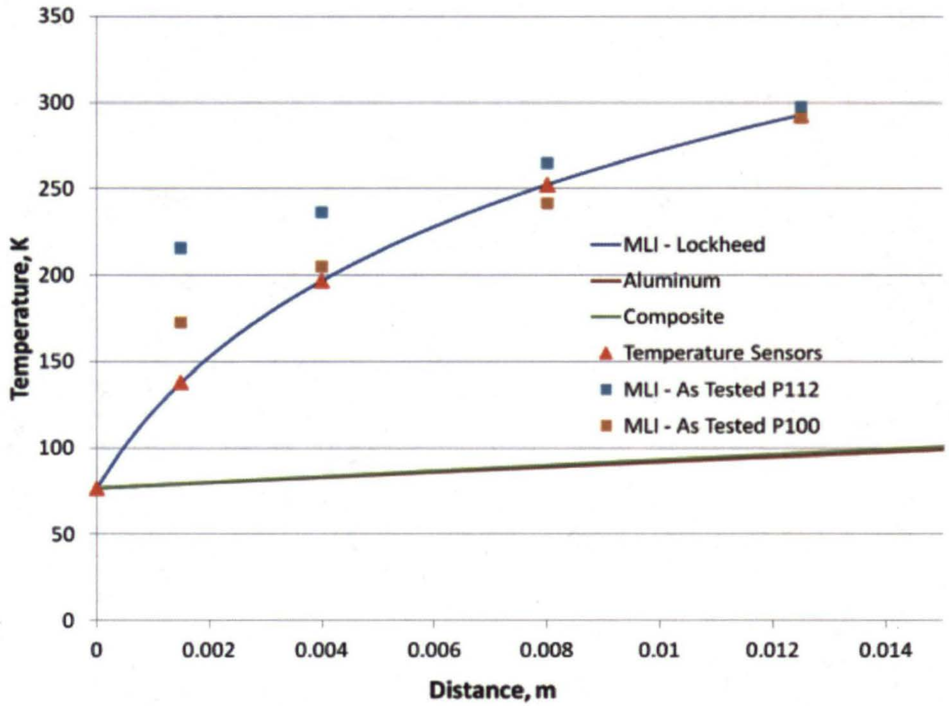
WBT (K)	Delta Heat Load (W)	Radius of Degradation (mm)
297	0.68	> 100
325	0.78	> 100

$$\frac{\Delta Q_1}{\Delta Q_2} = \left(\frac{T_{warm,1}}{T_{warm,2}}\right)^n$$

Results – Temperature Matching

- Used two different methods to determine length
  - Lockheed MLI equations & strut material properties
  - As tested temperatures from P112
- Temperature gradients shown to the right
- Increased WBT to 330 K on second test

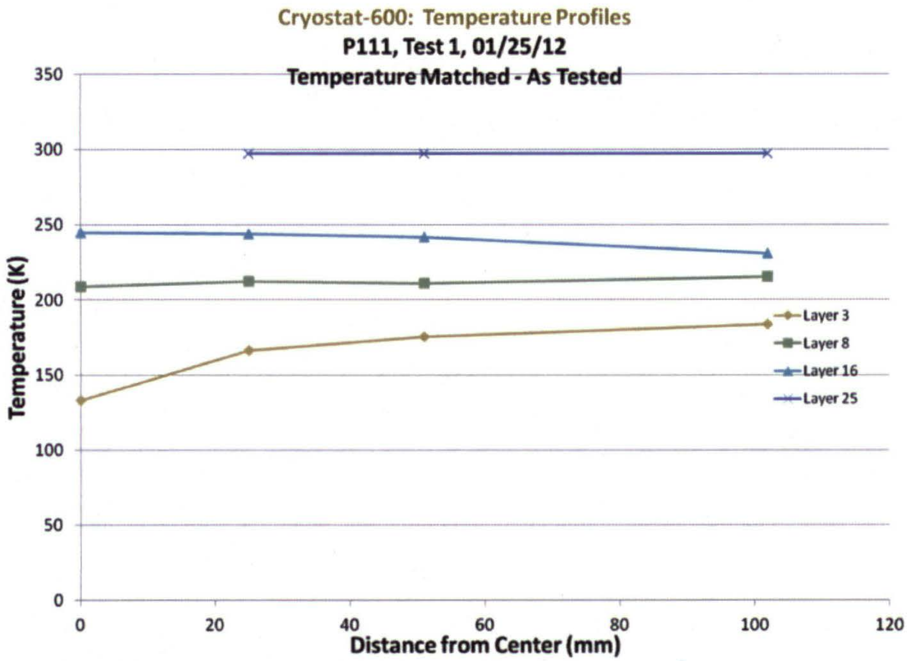
Layer #	Lockheed Strut Location (m)	As Measured Strut Location (m)
1	0.020	N/A
3	0.046	0.076
8	0.102	0.140
16	0.157	0.178
25	0.203	0.203

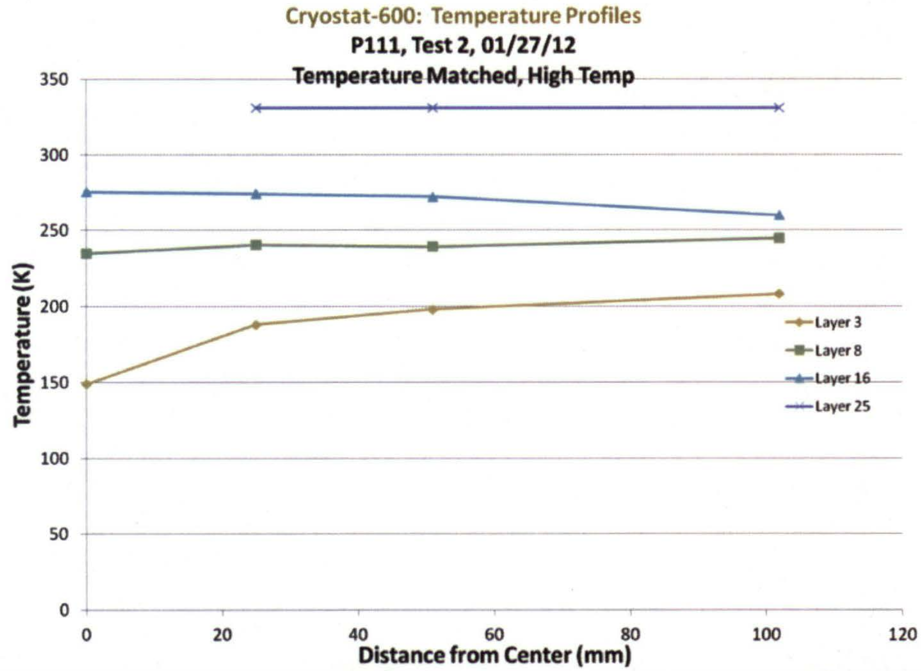


Results – Temperature Matching

- Initial testing using Lockheed data didn't perform well
- When modified locations to as tested data, got nearly optimal performance
- So, then increased heating to 330 K and got large increase in heat leak again

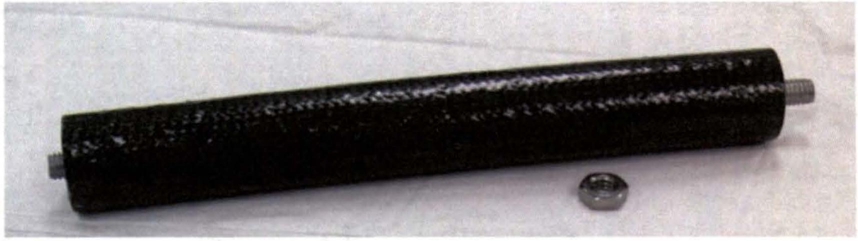
Test	ΔQ (W)	R (mm)	WBT (K)
Lockheed	0.783	>100	297
As Tested	0.010	50	297
As Tested	0.570	100	331



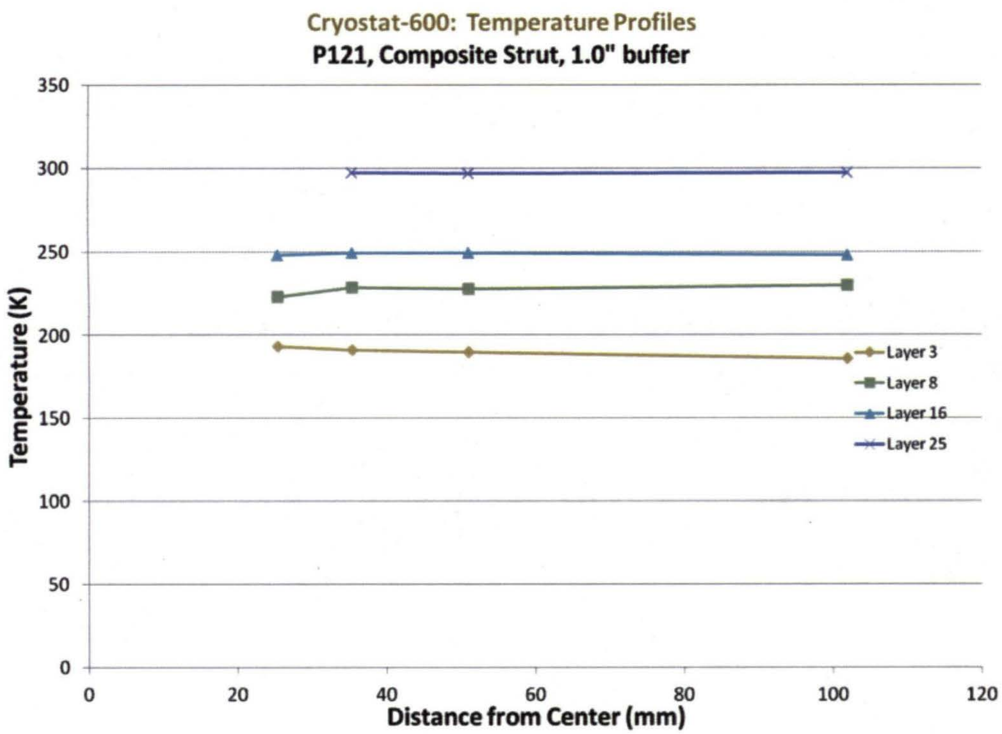


Results - Composite Strut

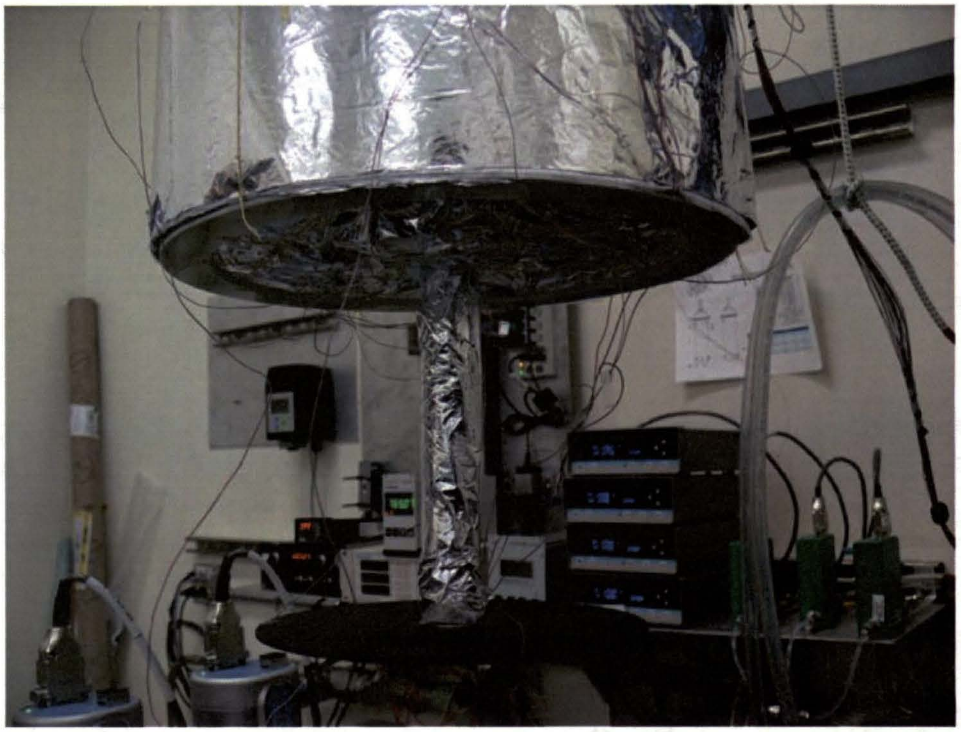
- Assumed similar thermal conductivity to IM2/977
- Made from 1K carbon & Araldite LY8604 Epoxy system on a 1" round mandrel (i.e. ID)
- Tested:
  - No Integration
  - 0.5" Cryolite Buffer
  - 1.0" Cryolite Buffer



Results – Composite Strut



Buffer Size (in)	ΔQ (W)	Radius (mm)
0	.31	>100
0.5	.256	51
1.0	.252	35



Results – Test Summary

Test #	Test Configurations	Date of Test	Vacuum Pressure	WBT	Punch Diameter (in)	delta Q	R-affect
			μ	K	0	W	mm
P100-1	No Penetration	10/04/11	5.81E–04	291.8	0	-0.005	>100
P101-1	Hot Poker	10/18/2011	7.00E-04	296.7	9/16	0.50	100
P101-2	Hot Poker	10/21/2011	4.70E-04	296.7	1 2/16	0.52	100
P102-1	0.5" strut, 0.5" aerogel blanket	10/26/2011	6.24E-04	300.8	1 2/16	0.779	35
P103-4	0.5" strut 0.5" Cryolite Buffer	11/4/2011	3.10E-04	296.5	1 2/16	0.75	51
P104-1	0.5" strut, 0.5"Vacuum Buffer	11/8/2011	4.03E-04	296.7	1 2/16	0.979	25
P105	0.5" strut, Aerogel Blanket (1")	12/1/2011	3.99E-04	296.5	1 10/16	0.942	35
P106-1	0.5" strut, Cryolite Buffer (1")	12/9/2011	5.71E-04	296	1 10/16	0.262	<25
P107	No Penetration	11/18/2011	2.34E-04	297.2	0	0	
P108	0.5" strut, Aerogel Bead Pack(1")	12/16/2011	1.38E-03	297	1 10/16	0.759	<25
P109	No Penetration	12/22/2011	5.12E-04	297.5	0		75
P110-2	Temp Matched - LM, 0.5" strut	1/12/2012	7.72E-04	297.6	1 1/16	0.759	>100
P111-2	Temp Matched - TD, 0.5" strut	1/24/2012	1.85E-03	296.6	1 1/16	0.01	50
P111-4	Temp Matched - TD, 0.5" strut	1/26/2012	9.50E-04	330.8	1 1/16	0.570	100
P112	No Penetration	1/31/2012	7.10E-04	297.3	0	0	25
P113	0.25" strut, 0.5"cryolite buff	2/8/2012	7.96E-04	296.9	14/16	0.200	25
P114	0.25" strut, 0.5" cryolite buff, disturbed	2/15/2012	4.57E-04	297.01	14/16	0.264	25
P115	0.25" strut, 1" buffer	2/22/2012	7.36E-04	296.6	1 5/16	0.288	< 25
P116	1.0" strut, 0.5" buffer	2/28/2012	7.53E-04	297.3	1 10/16	0.656	>100
P116-2	P116 at high temp	3/5/2012	1.18E-03	325.4	1 10/16	0.783	>100
P117	1.0" strut, 1.0" buffer	3/8/2012	6.25E-04	297.2	2	0.231	>100
P118	No Penetration	3/15/2012	2.41E-03	297	0	0.000	
P119	Composite Strut no buffer	3/22/2012	1.09E-03	296.3	1 1/16	0.305	>100
P120	Composite Strut, 0.5" cryolite buffer	3/30/2012	5.97E-04	296.9	1 10/16	0.256	51
P121	Composite strut, 1.0" cryolite buffer	4/9/2012	4.89E-04	296.9	2	0.252	35
P122	No Penetration	4/16/2012	5.42E-04	295.9		0.000	

Results – Model Summary

- **As a result of the model scaling, a multipart equation was developed**
- **Takes into account warm boundary temperature, MLI system # of layers, penetration diameter, and buffer thickness**

$$dq = q_{ref}\left(\frac{q_{actual}}{q'_{ref}}\right)_{\#layers}\left(\frac{q'_{ref}}{q_{ref}}\right)_{buffer\ thick}\left(\frac{q_{actual}}{q_{ref}}\right)_{diameter}\left(\frac{q_{actual}}{q_{ref}}\right)_{buffer\ thick}\left(\frac{T_h}{297}\right)^{1.56}$$

- **Requires the use of two reference states**
  - Recommend:
    Reference 1: 0.0762 m diameter penetration with 25 layers MLI, and 0.064 m buffer
    Reference 2 (or prime): 0.0762 m diameter, 25 layers, 0.127 m buffer
  - Alternate: use 0.1524 m diameter penetration for both with same other variables

Results – Model Sample Calculation

Calculate the degradation due to a 104 mm (4 inch) pipe going through 60 layers of MLI using an 8 mm (~0.75 inch) Cryolite buffer with a warm boundary temperature of 297 K.

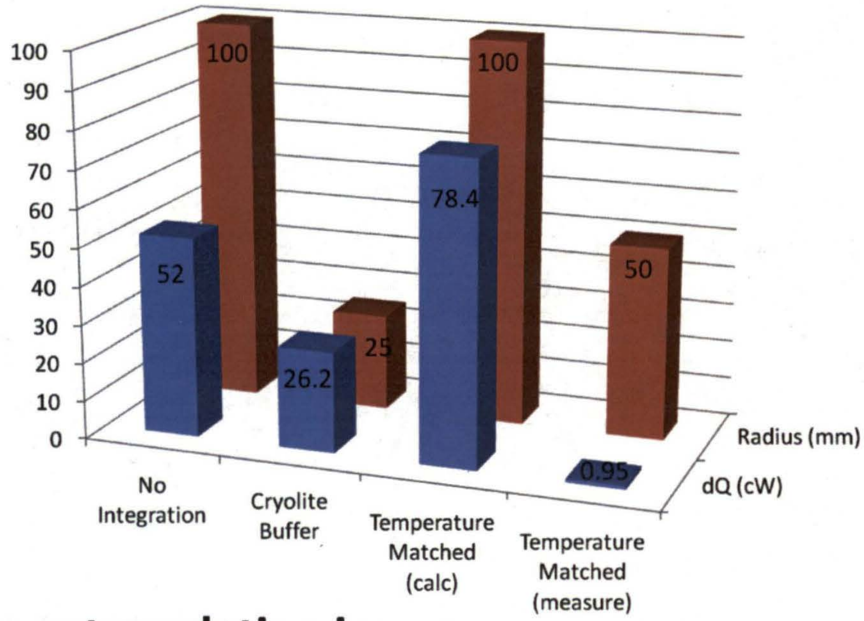
$$dq = q_{ref}\left(\frac{q_{actual}}{q'_{ref}}\right)_{\#layers}\left(\frac{q'_{ref}}{q_{ref}}\right)_{buffer\ thick}\left(\frac{q_{actual}}{q_{ref}}\right)_{diameter}\left(\frac{q_{actual}}{q_{ref}}\right)_{buffer\ thick}\left(\frac{T_h}{297}\right)^{1.56}$$

- **For reference case one use 25 layers of MLI with a 76.2 mm penetration and a 6.4 mm Cryolite buffer.**
  Qref equals 0.052 W from Slide 21.
- **For reference case two use 25 layers of MLI with a 76.2 mm penetration and a 12.7 mm Cryolite buffer. Qref' then equals 0.086 W from Slide 23.**
- **Q actual for the pipe diameter (using a 104 mm penetration with 25 layers of MLI & 6.4 mm Cryolite buffer) is 0.076 W from Slide 21.**
- **Q actual for the buffer thickness (using an 8 mm Cryolite buffer with 76.2 mm penetration and 25 layers) is 0.088 W from Slide 22.**
- **Q actual for the number of layers (using 60 layers with a 12.7 mm buffer and a 76.2 mm penetration) is 0.038 W from Slide 23.**
- **Since the WBT is 297 K, we can neglect the last term as 1**

$$dq = 0.052\left(\frac{0.038}{0.086}\right)_{\#layers}\left(\frac{0.086}{0.052}\right)_{buffer\ thickness}\left(\frac{0.076}{0.052}\right)_{diameter}\left(\frac{0.088}{0.052}\right)_{buffer\ thickness}$$
$$= 0.095W$$

Summary

- **Degradation radius (m) – the radius of the area of MLI degradation will be less than:**
  - Minimal Success: 0.05 m – met frequently
  - Full Success: 0.02 m – met with P113 & others
- **System delta Q (W) – the differential power input between the test and the undisturbed insulation + penetration conduction:**
  - Minimal Success: < 0.2 W – met with P113 (0.25" strut), P117 (1" strut very close)
  - Full Success: < 0.1 W – met with P111 (Temperature Matching)
- **Total of 22 Tests completed**
  - 5 no penetration
  - 3 no integration
  - 6 material trade study
  - 2 temperature matched
  - 6 strut size trade study
  - 3 composite strut
  - 1 MLI disturbance



- **Thermal model developed of test results**
- **Model validated and expanded to better gauge extrapolation issues**

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Questions

A more detailed paper about this work can be found online:
http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20120017916_2012018112.pdf